Exotic baryon states in QCD sum rule

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Abstract

It is shown, that the small decay width of $\Theta^+ = uudd\bar{s}$ baryon is suppressed by chirality violation. It is shown that Θ^+ decay width Γ is proportional to $\alpha_s^2 \langle 0|\bar{q}q|0\rangle^2$, for any pentaquark current without derivatives.

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In this talk we will discuss the the narrow exotic baryon resonance Θ^+ with quark content $\Theta^+ = uudd\bar{s}$ and mass 1.54 GeV. This resonance had been discovered last year by two groups [1, 2]. Later, the existence of this resonance was confirmed by many other groups, although some searches for it were unsuccessful. (see [3] for the review). Θ^+ baryon was predicted in 1997 by D.Diakonov, V.Petrov and M.Polyakov [4] in the Chiral Soliton Model as a member of antidecouplet with hypercharge $Y = 2$. The recent theoretical reviews are given in [5, 6]. Θ^+ was observed as a resonance in the systems nK^+ and pK^0. No enhancement was found in pK^+ mass distributions, what indicates on isospin $T = 0$ of Θ^+ in accord with theoretical predictions [4].

My talk is based mainly on our paper [7] and I try to explain some point of our paper more detailed. One of the most interesting features of Θ^+ is the very narrow width. Experimentally, only an upper limit was found, the stringer bound was presented in [2]: $\Gamma < 9MeV$. The phase analysis of KN scattering results in the even stronger limit on Γ [8], $\Gamma < 1MeV$. A close to the latter limitation was found in [9] from the analysis of $Kd \to ppK$ reaction and in [10] from $K + Xe$ collisions data [2]. The Chiral Quark Soliton Model gives the estimation [4]: $\Gamma_{CQSM} \lesssim 15MeV$ (R.E.Jaffe [11] claims that this estimation has a numerical error and in fact $\Gamma_{CQSM} \lesssim 30MeV$ – see, however, [12]). In any way, such extremely narrow width of Θ^+ (less than $1MeV$) seems to be very interesting theoretical problem. My talk will be organized in the following way: in the sect.1 I suggest the qualitative explanation of the narrow width of pentaquark and show that it is strongly parametrically suppressed. It will be shown, that the conclusion does not depend of the choice of the pentaquark current (without derivatives). In sect. 2 we will discuss the possible pentaquark currents and consider two-point correlation function.

Part 1.

In this section we will estimate the pentaquark width. Let us consider 3-point correlator

$$\Pi_\mu = \int e^{i(p_1 x - qy)} \langle 0 \mid \eta_\theta(x) j^5_\mu(y) \eta_n(0) \mid 0 \rangle \tag{1}$$

where $\eta_n(x)$ is the neutron quark current [?], ($\eta_n = \varepsilon^{abc}(d^a C\gamma_\mu d^b)\gamma_5\gamma_\mu u^c$),

$\langle 0 \mid \eta_n \mid n \rangle = \lambda_n v_n$, ($v_n$ and λ_n are nucleon spinor and nucleon transition constant into nucleon current eta_n), η_θ is arbitrary pentaquark current (not only Θ^+, but with other isospin also) $\langle 0 \mid \eta_\theta \mid \theta^+ \rangle = \lambda_\theta v_\theta$ and $j_{\mu 5} = \bar{s}\gamma_\mu\gamma_5 u$ is the strange axial current.

As an example of η_θ one can use the following one:

$$\eta_\Theta(x) = [\varepsilon^{abc}(d^a C\sigma_{\mu\nu} d^b)\gamma_\nu u^c \cdot \bar{s}\gamma_\mu\gamma_5 u - (u \leftrightarrow d)]/\sqrt{2}, \tag{2}$$

though all results in this section are the same for any pentaquark current (without derivatives). (Note, that this current have isospin 1, and I glad to thank M. Nielsen, who pay my attention to this, but for any current with isospin 0 and without derivatives results will be just the same).

As usual in QCD sum rule the physical representation of correlator (1) can be saturated by lower resonances (both in η_Θ and nucleon channel)

$$\Pi_\mu^{Phys} = \langle 0 \mid \eta_\theta \mid \theta^+ \rangle \langle \theta^+ \mid j_\mu \mid n \rangle \langle n \mid \eta_n \mid 0 \rangle \frac{1}{p_1^2 - m_\theta^2} \frac{1}{p_2^2 - m^2} + cont. \tag{3}$$

where $p_2 = p_1 - q$ is nucleon momentum, m and m_θ are nucleon and pentaquark masses.

Obviously,

$$\langle \theta^+ \mid j_\mu \mid n \rangle = g^A_{\theta n} \bar{v}_\theta \left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2} \right) \gamma^v \gamma_5 v_n \tag{4}$$

where axial transition constant $g^A_{\theta n}$ is just we are interesting in (the width is proportional to the square of this value). Such a method for calculation the width in QCD sum rules is not new, see, e.g. [?]. Substituting all these in eq (3) one can easily see, that 3-point correlator (1) is proportional to $g^A_{\theta n}$.

Let us neglect quark masses and perform the chiral transformation in (1) $q \longrightarrow \gamma_5 q$. It is evident, that η_n and $j_{\mu 5}$ are even under such transformation, while η_Θ is odd. Therefore, the correlator (1) vanishes in the limit of chiral symmetry. It is easy to see, that this statement is valid for any form of pentaquark and nucleon quark currents (spinless and with no derivatives). In the real world the chiral symmetry is spontaneously broken. The lowest dimension operator, corresponding to violation of chiral symmetry is $\bar{q}q$. So, the correlator (1) is proportional to quark condensate $\langle 0|\bar{q}q|0\rangle$. Just the same result one can found from direct calculation of invariant amplitude (at convenient kinematical structure, for example $\hat{p}p^\mu$). So we come to conclusion, that Θ^+ width is suppressed by chirality violation for any pentaquark current without derivatives(i.e. axial transition constant should be proportional to quark condensate).

The second source of the suppression also does not depend on the form of the pentaquark current. Let us again consider correlator (1). One can easily note, that unit operator contribution to this correlator (bare diagram) is expressed in the terms

of the following integrals

$$\int e^{i(p_1x-qy)}\frac{d^4xd^4y}{((x-y)^2)^n(x^2)^m} \equiv \int \frac{e^{ip_1x}}{(x^2)^m}\frac{e^{-iqt}}{(t^2)^n}d^4xd^4t \tag{5}$$

It is clear that such integrals have imaginary part on p_2^2 and q^2 - the momentum of nucleon and axial current - but there is no imaginary part on p_1^2 - the momentum of pentaquark. So we come to the conclusion that bare diagram correspond to the case, when there is no Θ^+ resonance in the pentaquark current channel (this correspond to background of this decay). (Note, that this conclusion don't depend on the fact that one of the quark propagators should be replaced by condensate, as we discuss before). The imaginary part on p_1^2 (i.e. Θ^+ resonance)appears only if one take into account hard gluon exchange. So we come to conclusion, that if Θ^+ is a genuine 5-quark state (not, say, the NK bound state), then in (2) the hard gluon exchange is necessary, what leads to additional factor of α_s. We come to the conclusion, that $\Gamma_\Theta \sim \alpha_s^2\langle 0|\bar{q}q|0\rangle^2$, i.e., Γ_Θ is strongly suppressed. This conclusion takes place for any genuine 5-quark states – the states formed from 5 current quarks at small separation, but not for potentially bounded NK-resonances, corresponding to large relative distances. There are no such suppression for the latters. I want to repeat once more, that this conclusion don't depend on the choice of current (without derivatives).

(I would like to add that recently (after this talk was given) in the paper of D.Melikhov and B.Stech [13], the pentaquark in the Chiral symmetry limit was investigated and authors note that they results agree with our conclusion about pentaquark width suppression due to chirality violation).

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References

[1] T.Nakano et al., Phys.Rev.Lett. **91**, 012002 (2003).

[2] V.V.Barmin, A.G.Dolgolenko et al., Yad.Fiz. **66**, 1763 (2003). (Phys.At.Nucl. **66**, 1715 (2003)).

[3] K.Hicks,hep-ph/0408001.

[4] D.Diakonov, V.Petrov and M.Polaykov, Z.Phys. **A359**, 305 (1997).

[5] D.Diakonov, hep-ph/0406043.

[6] V.B.Kopeliovich, Uspekhi Fiz.Nauk, **174**, 323 (2004)

[7] B.L.Ioffe, A.G.Oganesian, hep-ph/0408152 (2004)

[8] R.A.Arndt, I.I.Strakovsky and R.L.Workman, nucl-th/0311030.

[9] A.Sibirtsev, J.Heidenbauer , S.Krewald and lf-G.Meissner, hep-ph/0405099.

[10] A.Sibirtsev, J.Heidenbauer, S.Krewald and Ulf-G.Meussner, nucl.th/0407011.

[11] R.Jaffe, hep-ph/0401158,hep-ph/0405268.

[12] D.Diakonov, V.Petrov and M.Polyakov,hep-ph/0404212.

[13] D. Melikhov and B.Stech hep-ph/04090015 (2004).